Deep Space Networking Experiments on the EPOXI Spacecraft

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Abstract— NASA's Space Communications & Navigation Program within the Space Operations Directorate is operating a program to develop and deploy Disruption Tolerant Networking [DTN] technology for a wide variety of mission types by the end of 2011. DTN is an enabling element of the Interplanetary Internet where terrestrial networking protocols are generally unsuitable because they rely on timely and continuous end-to-end delivery of data and acknowledgments. In fall of 2008 and 2009 and 2011 the Jet Propulsion Laboratory installed and tested essential elements of DTN technology on the Deep Impact spacecraft. These experiments, called Deep Impact Network Experiment (DINET 1) were performed in close cooperation with the EPOXI project which has responsibility for the spacecraft. The DINET 1 software was installed on the backup software partition on the backup flight computer for DINET 1. For DINET 1, the spacecraft was at a distance of about 15 million miles (24 million kilometers) from Earth. During DINET 1 300 images were transmitted from the JPL nodes to the spacecraft. Then, they were automatically forwarded from the spacecraft back to the JPL nodes, exercising DTN's bundle origination, transmission, acquisition, dynamic route computation, congestion control, prioritization, custody transfer, and automatic retransmission procedures, both on the spacecraft and on the ground, over a period of 27 days. The first DINET 1 experiment successfully validated many of the essential elements of the DTN protocols. DINET 2 demonstrated: 1) additional DTN functionality, 2) automated certain tasks which were manually implemented in DINET 1 and 3) installed the ION SW on nodes outside of JPL. DINET 3 plans to: 1) upgrade the LTP convergence-layer adapter to conform to the international LTP CL specification, 2) add convergence-layer "stewardship" procedures and 3) add the BSP security elements [PIB & PCB]. This paper describes the planning and execution of the flight experiment and the validation results.

I. Introduction

Disruption-Tolerant Networking (DTN; a.k.a. Delay-Tolerant Networking) is a communication architecture that is designed to provide automated data communication services in networks characterized by frequent and lengthy episodes of partitioning, lengthy signal propagation delays, and/or heterogeneity in protocol support below the application layer.

Research into DTN has culminated in the publication of Internet experimental RFCs (Requests For Comments) describing the overall architecture of DTN technology (RFC 4838), the core DTN Bundle Protocol (RFC 5050), and the Licklider Transmission Protocol for automatic retransmission of data lost in transit (RFC 5326), with others in progress. Although this research has been substantially motivated by its applicability to such problem domains as sensor-based networks with scheduled intermittent connectivity, terrestrial wireless networks that cannot ordinarily maintain end-to-end connectivity, and underwater acoustic networks, the original driver for the research was the emerging need to provide capable network services in support of space flight operations.

Historically, communications in spacecraft mission operations have been managed by the spacecraft team. Transmission and reception episodes are individually configured, started, and ended by command. Reliability over deep space links is achieved by management, i.e. on loss of data, we command retransmission. Even the relaying of data from Mars rovers through Mars orbiters is managed, i.e. we send transmission commands to the rovers, and later we send transmission commands to the orbiters that received the data from the rovers.

An alternative approach would be to implement an automatic space data communications network, similar in capability to the Internet. The Internet protocols themselves, however, are generally unsuitable for this purpose because they rely on timely and continuous end-to-end delivery of data and acknowledgments. Communications links to and from spacecraft are often subject to interruption and, for deep-space missions, signal propagation delays may be very large.

DTN is an alternative network architecture that is designed to address these problems. DTN runs as an “overlay” above the Internet where possible, but it runs directly over link-layer protocols, taking the place of the IP network protocol where necessary. That is, a TCP connection within an IP-based network may be one “link” of a DTN end-to-end data path; a deep-space R/F transmission may be another. Reliability is achieved by retransmission between relay points within the network, not end-to-end retransmission. There is no reliance on end-to-end acknowledgment. Route computation has temporal as well as topological elements, e.g., a schedule of planned contacts. Lengthy signal propagation delays don’t compromise the accuracy of route computation. Forwarding at each router is automatic but not necessarily immediate: store-and-forward rather than “bent pipe”, so link interruption doesn’t prevent the eventual delivery of data.

DTN offers significant promise for better utilization of existing bandwidth and improved end-user satisfaction. A significant strategic result with both immediate and future consequences is a reduction in the reluctance within the space-flight operations community to host networking technology with a high (if not complete) degree of autonomy. DTN provides the ability of a space network to exchange data between its constituent nodes with Internet-like automation and the resultant low operations labor costs. As networks grow in complexity, the time and effort needed to manually schedule and coordinate link activity quickly becomes unmanageable. DTN allows space networks to scale without such constraints. In addition, the ability to automatically route information between space vehicles in local proximity without incurring the potentially long one-way light time delays and Earth-based decision cycles of human-managed communications offers the possibility of new types of coordinated science that qualitatively differ from current capabilities. DTN can help enable cooperative, reactive science functionality for remote spacecraft networks.

The JPL Interplanetary Overlay Network (ION) software is an implementation of the DTN architecture that is specifically intended to be usable for interplanetary communications. As such, a key milestone in its development has been validation in operation on-board a functioning spacecraft. The Deep Impact Network [DINET] experiments provided an opportunity not only to validate the software in flight but also to apply metrics by which the operational suitability of the software could be objectively assessed.

II. DINET Overview

A. Program Level Summary

The Deep Impact Network [DINET] experiments are a series of technology validation activities of JPL’s implementation of Delay-Tolerant Networking (DTN) protocols. The experiments produced versions of JPL’s implementation of Delay-Tolerant Networking protocols [ION] in flight and ground software. The experiments include the following partners and contractors the Johns Hopkins University Applied Physics Laboratory (APL), the NASA EPOXI project, Colorado University and Ball Aerospace and Technology Corporation. The flight segment of the DINET experiments was implemented on the Deep Impact spacecraft and was closely coordinated with the EPOXI project. The ground segment of the experiments was implemented in the JPL deep space multi mission operations environment and the specific adaptations of those applications for the EPOXI project. The technology [as opposed to the operational] aspects of the experiments were monitored by the DINET Experiment Operations Center implemented in the JPL Protocol Test Laboratory. The DINET experiments are sponsored by NASA Office of Space Operations / Space Communications and Navigation (OSO/SCAN) via JPL DSN office Space Networking and Mission Automation.

A key aspect of the DINET experiments was the development of the software to the quality of operational flight software so that future flight projects can easily use it at low risk. The DINET software was implemented consistent with the JPL requirements for class B flight software. The APL development of the Bundle Security Protocol software was developed to similar requirements. Institutional software quality at JPL and APL monitored the respective software developments in order to ensure both development efforts met quality standards and mission objectives.

B. Deep Impact Spacecraft Summary

The Deep Impact spacecraft operated by the EPOXI project was a unique opportunity to demonstrate the DTN technology. The DI spacecraft has a backup flight computer which is always on and available for communications. The prime flight computer controls all spacecraft functions, even while communication with the ground is through the backup flight computer. The DI spacecraft already had the CFDP protocol implemented for file transfer to and from the ground.

The EPOXI project was able to benefit from the DINET experiments and had the personnel available for flight software implementation and test, as well as spacecraft operations during the experiments. DINET developments and operations were on a non-interference basis with EPOXI to the maximum extent possible. It was critical to the EPOXI project that the DINET experiments pose minimal risk to the EPOXI mission. The EPOXI flight team worked closely with the DINET team to design an implementation approach that minimized risk to the spacecraft.

C. DINET Experiment Operations Center (EOC).

An essential component of the DINET experiments is the Experiment Operations Center (EOC). The EOC implemented the following functions.

1. Produce experiment payload data, i.e. input JPEG image files as a single file per bundle, mark bundle priority and meter output to specified data rate.
2. Consume experiment payload data, i.e. store in local file system at node upon reception and display image upon reception.
3. Consume software diagnostic messages (ION logs), i.e. ION log messages were transmitted to EOC software via TCP/IP socket and received messages were parsed & stored in a SQL database.
4. Consume protocol diagnostic messages (BSRs), i.e. BSRs transmitted from ION nodes to EOC software via the ION stack and received messages were parsed & stored in an SQL database.
5. Monitor EOC bundle network, i.e. BSRs transmitted from ION nodes to EOC software via the ION stack and received messages parsed & stored in a SQL database. Messages were displayed through the GUI in real time.

The EOC generated and received the test communications traffic as well as "out-of-DTN band" command and control traffic of the DTN experiment, stored DTN flight test information in a database, provided display systems for monitoring DTN operations status and statistics (e.g., bundle throughput), and supported query and analyses of the data collected. The DINET EOC was located within the JPL Protocol Technology Lab (PTL). The PTL provides connectivity to other NASA centers and external entities, and is itself a node in the larger DTN Experiment Network (DEN).

III. DINET 1

The basic topology of DINET 1 is shown in Figure 1 (i.e., two surface assets, a relay orbiter, and Earth). The surface assets are designated Mars and Phobos, and the Deep Impact (DI) spacecraft fills the role of the relay orbiter. Figure 2 shows how this topology was implemented during the experiment. The ION software with the DTN protocols was resident in each of the eleven circles, i.e. network nodes. All the nodes, except for the Deep Impact spacecraft [node 7], were physically located in the JPL Deep Space Operations Team (DSOT) area or in the Protocol Test Laboratory.

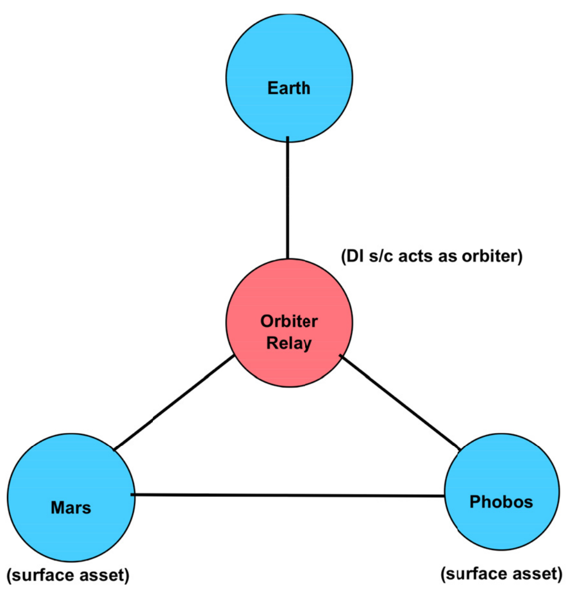


Figure 1 DINET 1 Network Topology

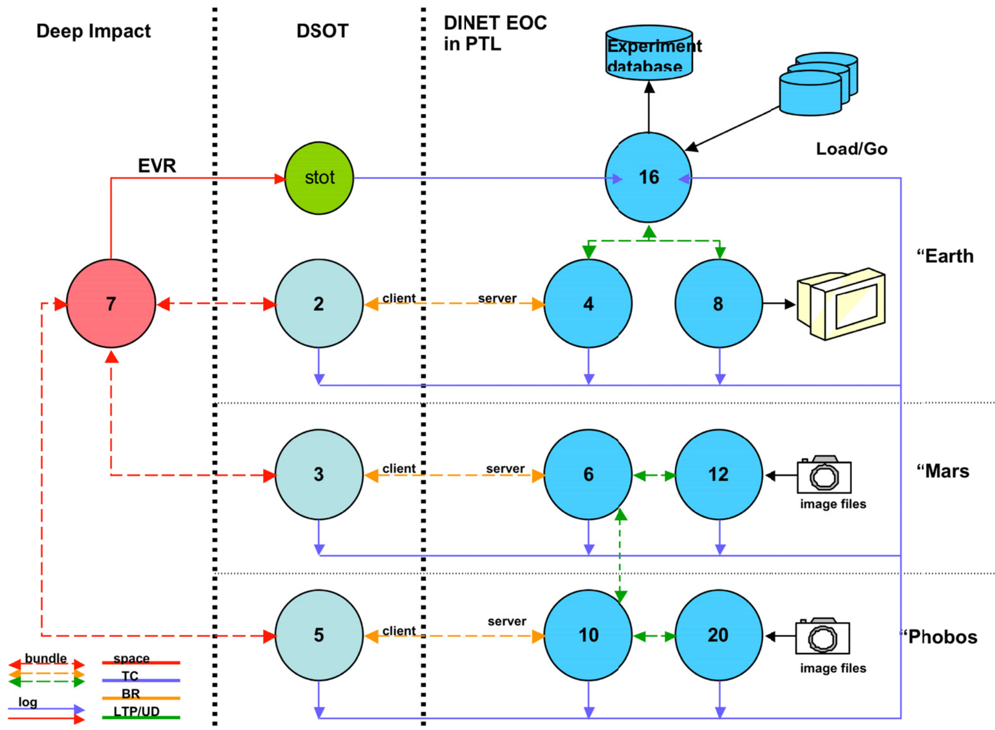


Figure 2 DINET 1 Topology as Physically Implemented BRS = Bundle Relay Service; LTP = Licklider Transmission Protocol; UDP = user datagram protocol

The 4-week period of DINET operations was divided into two configurations (*a* and *b*) of four tracking passes each. Configuration *a* had no injection of artificial data loss. During configuration *b*, 3.125% of all LTP segments were randomly discarded upon reception at the DI spacecraft and at each of the three DSOT nodes. On the fourth tracking pass of each segment, the contact between Phobos and EPOXI was omitted. A brief "cross-link" contact between Phobos and Mars was scheduled for a time shortly before the 4th tracking pass of each experiment, providing an alternate path for data from Phobos. Four paths (topology experiments) were navigated using the setup shown in Figure 2.

The DINET 1 software was installed on the backup software partition on the backup flight computer. Once the backup flight computer was booted with the DNET software, the boot configuration was restored to the original EPOXI software load. In the event of a spacecraft problem requiring a flight computer side swap, the backup computer with the DIINET software would be re-booted as prime, with the original EPOXI software running. EPOXI operations during the month of DINET 1 operations was performed by uploading a sequence to the spacecraft, which would switch the telemetry source to the SDST between the prime and backup flight computers, corresponding to the contact graph intervals installed during the DINET 1 software upload. This made spacecraft operations "hands-off" during the DINET 1 operational passes. The EPOXI flight control team would switch the updated DINET 1 ground system software into place during the DINET 1 operational passes and turn over the data-link to the DINET 1 operations team. DINET 1 operations were performed during the EPOXI spacecraft team"stand down" after during October and November 2008).

During the experiment, the spacecraft was at a distance of about 15 million miles (24 million kilometers) from Earth. DINET 1 demonstrated the first instance of an "interplanetary network" on October 20, 2008 when images were successfully received at JPL from the Deep Impact spacecraft located approximately 80 light seconds from Earth. These same images had been transmitted to the Deep Impact spacecraft about 3 hrs earlier via the same network. During DINET 1 some 300 images were transmitted from the JPL nodes to the spacecraft. Then, they were automatically forwarded from the spacecraft back to the JPL nodes, exercising DTN's bundle origination, transmission, acquisition, dynamic route computation, congestion control, prioritization, custody transfer, and automatic retransmission procedures, both on the spacecraft and on the ground, over a period of 27 days. All transmitted bundles were successfully received, without corruption, despite several transient unanticipated lapses in service at Deep Space Network (DSN) stations during tracking passes. Complete, detailed discussions of the results of DINET 1 are included in reference 1.

IV. DINET 2

DINET 1 successfully validated many of the essential elements of the Disruption Tolerant Network DTN] protocols. DINET 2 was designed to: 1) validate additional DTN functionality, 2) automate certain tasks which were manually implemented in DINET 1, 3) install the ION SW on nodes outside of JPL and 4) exercise the DTN protocols in flight and ground systems with simulated network traffic and analyze the results. The implementation of the Bundle Security Protocol [BSP] is included in item 1 and is enabling for operational use of DTN on NASA missions. Figure 3 presents the DINET 2 topology implemented during the experiment. The key changes from DINET 1 include the inclusion of experiment nodes outside of the JPL firewall specifically at APL and UC Boulder and their DTN node on the International Space Station.

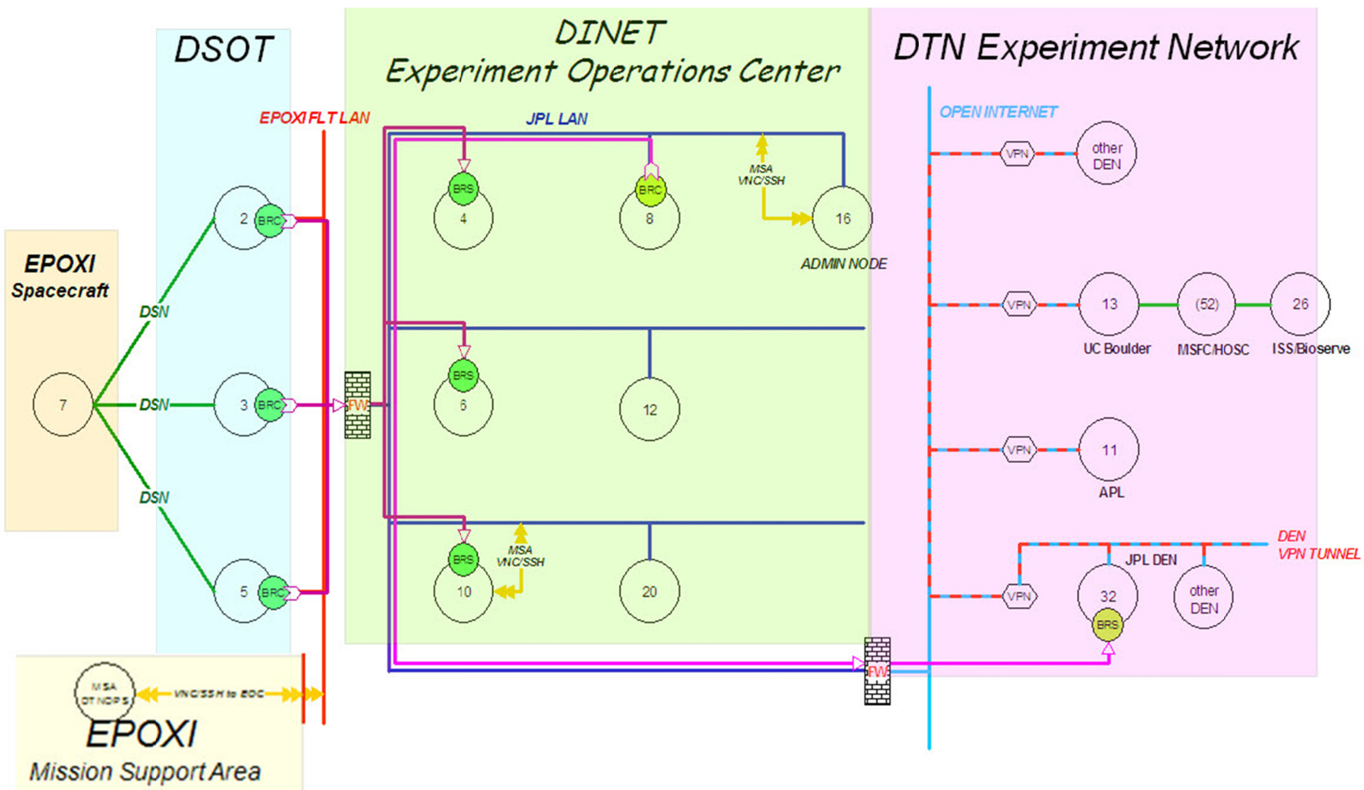


Figure 3 DINET 2 physical topology

The BSP flight software was provided by APL. Colorado University provided the interface between the DEN and their DTN node on the International Space Station. BATC provided the Deep Impact flight software modified to include the DTN features as they had done for DINET 1.

As was done in DINET 1, there would be a series of DSN tracking passes each with duration of about 4 hrs and two passes per week. The plan was to use 8 passes for the demonstration and validation of the additional DTN functionality as follows.

- Passes 1 and 2: repeat of DINET 1 to establish baseline performance
- Passes 3 and 4: turn on automated file transfer for EPOXI and repeat passes 1 & 2
- Passes 5 and 6: repeat passes 3 & 4 with BSP
- Passes 7 and 8: repeat passes 5 & 6 with a non JPL node

As was done for DINET 1, the EPOXI project has full responsibility for the flight and ground systems and will be responsible for all communications to JPL/NASA management regarding health, performance and risk of the project. The EPOXI project manager, mission manager, spacecraft team chief and spacecraft team personnel all retain their project responsibilities during DINET operations. The uplink and downlink data paths using during the DINET experiment are the same as during normal EPOXI operations with the additional of the DINET EOC which acts as a remote science or instrument operations centers. DTN software is uploaded to, and executed on, the EPOXI spacecraft's backup flight computer (SCU-B) only. The EPOXI GDS [ground data system] is used. During DINET 2, the EPOXI operations teams are all functioning as they would during any EPOXI operations. During the demonstration and validation of the new DTN functionality, the experiment is operated by the DINET team in the EOC with the EPOXI team carefully monitoring the experiment.

The primary DINET 2 objective is to demonstrate secure DTN network operations between multiple different ground networks and multiple space based nodes. The following are the eight detailed technical objectives of DINET 2.

1. Validate use of BSP for data transfer
2. Validate use of BSP in discriminating against unsecured traffic
3. Validate the ability to change BSP keys and policies during operations
4. Utilize bundle examiner to inspect bundles arriving at the EOC
5. Collect CPU utilization data on the SCU with BSP Tx policy on and off
6. Demonstrate the robustness of DTN software for use across nodes at multiple institutions in an operational scenario
7. Validate the DTN effectiveness in an operational scenario

The fundamental operation during DINET 2 was to send images from the EOC to APL via EPOXI and to send a simulated solar flare warning message from the EOC to ISS via EPOXI. Various message priority and security settings were exercised during these file transfers. Due to certain software development issues the DINET 2 software was not loaded onto the spacecraft. The software issues were later resolved and the software was loaded onto the EPOXI test bed which simulated the spacecraft and the operations described above were perform. The following success criteria were achieved.

1. Data flows across the network as expected
2. BSP behaves as anticipates in filtering out unsecure traffic and allowing secure traffic.
3. Bundle examiner is able to inspect the contents of each incoming bundle.
4. Procedures are followed.
5. CPU utilization statistics are obtained.

In summary DINET 2 flowed DTN network traffic, securely across multiple firewalls from/to JPL, APL, EPOXI test bed and ISS via CU.

V. DINET 3

DINET 3 is planned to be the third effort to exercise the Delay/Disruption Tolerant Networking (DTN) protocols on the Deep Impact spacecraft. DINET 1 demonstrated the first instance of an "interplanetary network". DINET 2 extended the network outside the JPL firewall to APL and the International Space Station. DINET 3 objectives are: 1) develop extensions to DTN flight and ground software [includes [CFDP and AMS]/BP/LTP/TM-TC with BSP], 2) demonstrate the flight-qualified, operations-ready DINET 3 DTN elements, and 3) install operational (TRL 9) DTN software on the Deep Impact flight and ground systems. In full partnership with the Deep Impact spacecraft team, DINET 3 plans to develop, test, and install DTN software on the Deep Impact flight and ground systems to enable reliable, robust file transfers using existing Deep Impact command, telemetry, and file delivery systems. DINET 3 FSW will be installed on the primary flight computer and used to support all normal operations of the Deep Impact spacecraft. DINET 3 operations are planned to begin in October 2011. The members of the DINET 3 team include APL, BATC, the EPOXI project and the JPL DINET team.

The DINET 3 operations scenarios are driven by the objective to develop an integration of the ION DTN software with the Deep Impact spacecraft software "ASPEN" to enable reliable, robust file transfers using existing Deep Impact command, telemetry, and file delivery systems. As such it is all about file transfers, up and down. During DINET 3, the Deep Impact operations teams are all functioning normally and they will be in full control of the files sent and retrieved from the spacecraft via the DTN software. The sequence of file transfers will be planned, tested and reviewed and approved by Deep Impact personnel before operations. File uplink will be initiated via the FDM system in Deep Impact's GDS, just as when Deep Impact's native CFDP implementation is exercised in routine mission operations; FDM will be integrated with the new DINET CFDP implementation for this purpose. File downlink will be initiated via spacecraft command as in routine mission operations. The sequence of these activities will go through the normal Deep Impact design, test, review and approval process. All files retrieved from the spacecraft will be the responsibility of the Deep Impact spacecraft team and will be handled like any other science data. During the file transfer operations, the DINET 3 team will be exercising the new elements of BSP in order to demonstrate TRL 9 for those elements of DTN. The BSP activities are intended to be transparent to the Deep Impact spacecraft team file transfer activities. Operational constraints from the Deep Impact spacecraft team include: 1) the flight team should use existing techniques to modify DTN functionality and 2) the flight team should have visibility into DTN settings.

DINET 3 Operations will be implemented in three distinct phases: Technology Validation, Deep Impact Validation, and Deep Impact Operations.

The **Technology Validation** phase exercises new BSP implementations, etc., in a DINET-1-like network in EOC, reestablish DINET-I baseline, raises DTN elements (e.g. BSP) to TRL to 8 and ION operates on SCU-B/B:> using heritage DINET GDS configuration. During this phase the associated network diagnostic will be collected in the EOC, will be analyzed by the DINET 3 team, and will be part of the DINET 3 final experiment report.

The **Deep Impact Validation** phase exercises file transfer abilities through the EPOXI-DSOT-only network in order to safely determine FSW can be installed on SCU-A. This phase exercises EPOXI network ops functionality by including the following elements.

- Telemetry from on-board DTN node [#7]
- Commands to manage on-board DTN node
- “Monitor” data from DSOT DTN node [#2]
- Perform file transfer exercises per EPOXI
- Change GDS configuration by removing EOC and DSOT nodes 3, 5 and managing operations at DSOT
- On-board BSP will be disabled
- ION FSW operates on SCU-B/B:> using EPOXI-DSOT-only configuration

During the third phase, **Deep Impact Operations**, the DINET 3 flight software will be loaded onto the prime computer and the remaining elements of the system are now exercised by the Deep Impact Spacecraft team in their operational environment achieving, for those elements, TRL 9. Table 1 summarizes the current plans for DINET 3 operations.

Ops Phase	Technology Validation				Deep Impact Validation			Deep Impact Operations			
Week	1	1	1	2	3	4	5	6	6	7	8
DSN Passes		1	2	3, 4	5, 6	7, 8	9, 10	11	12	13, 14	15, 16
GDS Config	EOC M&C	-->	-->	-->	Deep Impact Ops	-->	-->	-->	-->	-->	-->
Network Topology	11 Node Network	-->	-->	-->	2 Node Network	-->	-->	3 Node Network	-->	-->	-->
SCU – A Partition – B	Boot 8.02	-->	-->	-->	-->	-->	-->	Boot DINET 3	-->	-->	-->
SCU – A Partition – F	Backup 8.02	-->	-->	-->	-->	-->	-->	-->	-->	-->	-->
SCU – B Partition – B	Boot 8.03	Boot DINET 3	-->	-->	-->	-->	-->	-->	-->	-->	-->
SCU – B Partition – F	Backup 8.03	-->	-->	-->	-->	-->	-->	-->	-->	-->	-->
Operations		Load DINET3 FSW to B/B	Establish DINET 1&2 functions	BSP tests	Nominal up & down file transfers	Testing various DL/UL configurations	Off Nominal up & down file transfers	Load DINET3 FSW to A side	DI TBD	DI TBD	DI TBD

Table 1 DINET 3 Operations Summary

VI. Summary

DTN has been matured in a series of events, experiments and demonstrations. The Deep Impact Network [DINET] series of tasks has produced a version of JPL's implementation of the DTN protocols in flight and ground software that is now at technology readiness level (TRL) 8 and is planned to go to 9, see table 2. DINET can be appreciated through two complementary perspectives. The first is technical significance. Prior to DINET 1, the team defined four validation metrics, each of which was achieved during the experiment. The technical significance of DINET 1 relies on the quantitatively defensible and tangible results. In summary, the Bundle and Licklider Transmission protocol elements of DTN were rigorously proven to work, as expected, in the disruptive environment of an interplanetary mission.

The second perspective takes a broader, longer view, concentrating on the strategic significance of the DINET experiments. It addresses the broader questions of the importance of the experiment's achievements, in both current and future timescales. The experiments' successful demonstration of the priority-aware relay aspect of DTN offers significant promise for better utilization of existing bandwidth and improved end-user satisfaction. A significant strategic result with both immediate and future consequences is a reduction in the reluctance within the space-flight operations community to host networking technology with a high (if not complete) degree of autonomy. Indeed, the EPOXI spacecraft team itself had to be convinced that the DTN software and operations plan posed no serious threat to the safety of their spacecraft. The EPOXI project team currently is an advocate for DTN functionality on their spacecraft.

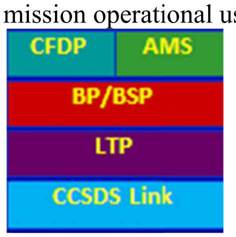
DINET Experiment Content	Participants and *Status*	TRL Maturity
DINET-1: Flight Validation of Core DTN • Priority • Dynamic Routing • Automated Forwarding • Custody Transfer • Delay-Tolerant Retransmission • Flow & Congestion Control	JPL Ball Aerospace and Technology Corporation and the NASA EPOXI project *300 images were transmitted from JPL to EPOXI and automatically forwarded back to JPL, exercising DTN's bundle origination, transmission, acquisition, dynamic route computation, congestion control, prioritization, custody transfer, and automatic retransmission procedures, both on the spacecraft and on the ground, during Oct/Nov '09. All transmitted bundles were successfully received, without corruption*	Early DTN core at TRL 7-8 for deep space missions
DINET 2: Flight Validation of DTN Enhancements for Mission Operations • DTN with unacknowledged CFDP overlay • Bundle Security Protocol (BSP) • Dynamic Contact Graph Management • Demo Multiple ION Network Nodes • Extended Priority System • Potential use by EPOXI ops team to transfer science files using DTN	EPOXI, APL, Ball Aerospace, JPL, CU *DTN network traffic, securely across multiple firewalls from/to JPL, APL, EPOXI test bed and ISS via CU.*	BP/LTP and BSP at TRL 7 for deep space missions
DINET-3: Flight validation of enhanced DTN stack in actual space mission operational use 	EPOXI, APL, Ball Aerospace, JPL *Planned but not yet implemented*	Flight DTN core software in operational use for deep space missions (DTN @ TRL 9)

Table 2 Summary of DINET Experiments

DINET showed the ability of a space network to exchange data between its constituent nodes with Internet-like automation and the resultant low operations labor costs. As networks grow in complexity, the time and effort needed to manually schedule and coordinate link activity quickly becomes unmanageable; DTN allows space networks to scale without such constraints. In addition, the ability to automatically route information between space vehicles in local proximity without incurring the potentially long one-way light time delays and Earth-based decision cycles of human-managed communications offers the possibility of new types of coordinated science that qualitatively differ from current capabilities. DTN can help enable cooperative, reactive science functionality for remote spacecraft networks.

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